Chin. J. Astron. Astrophys. Vol. 6 (2006), **Suppl. 2**, 193–196
(*http://www.chjaa.org*)

Chinese Journal of
Astronomy and
Astrophysics

Can Pulsars be used to Probe Quantum Gravity?

H. S. Knight † ⋆

Centre for Astrophysics and Supercomputing, Swinburne University of Technology, P.O. Box 218, Hawthorn VIC 3122, Australia

Abstract Several radio pulsars have now been shown to emit giant pulses that align in phase with high energy emission rather than with their integrated pulse components. We investigate whether timing of giant and γ-ray pulses can be used to improve limits on the energy scale of quantum gravity by placing bounds on the energy dependence of the speed of light. We find good sources for this experiment are putative Crab-like pulsars in M31, which should in principle be detectable by the current generation of radio telescopes. However, the detection of pulsed emission from their γ-ray counterparts seems unlikely in the near future.

Key words: pulsars: general — pulsars: individual (PSR B1937+21, Crab Pulsar) — gravitation — gamma rays:theory

1 INTRODUCTION

No complete quantum theory of gravity has yet been formulated, and so the energy scale at which quantum gravitational effects become important ($E_{\rm QG}$) is unknown. Some theories, such as those that have large extra dimensions, predict values of $E_{\rm QG}$ much less than the Planck energy, $E_{\rm P} \sim 10^{19}$ GeV (Burgess et al. 2002; Jacobson, Liberati, & Mattingly 2003). Establishing limits on $E_{\rm QG}$ is one way of ruling out competing models of quantum gravity and their associated phenomenology.

In some theories of quantum gravity a particle propagating through a vacuum will have a finite cross section for scattering from the quantisations of gravitational vacuum fluctuations (see e.g. Amelino-Camelia et al. 1998; Ellis et al. 2000). In the simplest perturbative approach, the cross section for a particle undergoing such an interaction and consequently being delayed will be first order in $E/E_{\rm QG}$, where E is the energy of the particle. Therefore observational limits on *in vacuo* dispersion provide bounds on $E_{\rm QG}$ for these theories.

Jacobson, Liberati, & Mattingly (2003) obtained a first-order limit of $E_{\rm QG} \geq 10^{26}$ GeV by considering synchnotron radiation from the Crab nebula. This result effectively ruled out first-order theories for which the maximum attainable velocity for high-energy electrons is less than the speed of light (c), but did not place bounds on theories for which only photons have modified dispersion laws (Ellis, Mavromatos, & Sakharov 2004). Limits on these theories can be obtained by observing photons of different energies arriving simultaneously from a distant astrophysical source. The delay between two such photons is:

$$\Delta t \sim \frac{\Delta E}{E_{\rm QG}} \frac{L}{c}. \quad (1)$$

Here ΔE is the difference in energy of the photons and L is the pathlength.

The best limit obtained through this class of experiment is that of Boggs et al. (2004). A flare within a very strong gamma-ray burst (GRB) was observed to have a time drift of less than 4.8 ms from 3 to 17 MeV. At 1.3 Gpc this GRB gave a first-order limit of $E_{\rm QG} \geq 1.8 \times 10^{17}$ GeV.

† Affiliated with the Australia Telescope National Facility, CSIRO
⋆ E-mail: hknight@astro.swin.edu.au

In this paper we revisit whether improved bounds on $E_{\rm QG}$ can be obtained through high-energy observations of pulsars. We suggest that phase correlations between giant pulses in the radio band and high-energy pulses can be used to improve limits, and discuss the use of giant pulses in finding more distant sources suitable for travel-time experiments.

2 WAYS OF IMPROVING PULSAR-DERIVED LIMITS ON QUANTUM GRAVITY

Kaaret (1999) timed the Crab pulsar using bands of median energy 82.8 MeV and 2.93 GeV using the Energetic Gamma-Ray Experiment Telescope (EGRET) aboard the Compton Gamma-Ray Observatory. Kaaret's measurement of arrival times differing by no more than 350 μs for emission travelling 2 kpc yields a limit of $E_{\rm QG} \geq 1.7 \times 10^{15}$ GeV.

Kaaret was limited by the sensitivity of EGRET to photons with energies above 2 GeV. The highest energy that the Crab pulsar emits pulsed radiation is in the range of 10–60 GeV (Fierro et al. 1998; de Naurois et al. 2002). Given current bounds on $E_{\rm QG}$, the lack of pulsations above this energy range is inconsistent with a complete smearing of the pulse profile due to quantum gravitational effects. The cutoff is instead explainable by models of pulsar emission (Romani 2003). Future γ-ray missions such as GLAST[1] will have better photon statistics and operate at higher energies than EGRET. Using $\sim$10 GeV photons GLAST may improve the Crab-derived limit by $\sim 10^2$.

Arrival time estimates can also be improved by observing a pulsar with a narrower profile. The millisecond pulsars (MSPs) B1937+21 and J1824$-$2452 respectively have X-ray pulses that are $\sim$30 μs wide (Cusumano et al. 2003; Rutledge et al. 2004). The discovery of correspondingly narrow γ-ray components from these MSPs could give improvements in γ-ray timing and on-pulse photon statistics suitable for placing better limits on $E_{\rm QG}$.

Giant pulses in the radio band could also be used to improve limits. For pulsars where poor photon statistics do not allow more than a single profile to be formed, the alignment in pulse phase of radio giants and high-energy pulses (see e.g. Knight et al. 2006) could be exploited so as to provide a zero-phase for the γ-ray pulse-profile. Such a technique would require improved knowledge of which types of pulsars have aligned giant pulses and high energy emission.

The intrinsic timescale of giant pulses emission appears to be $\leq$ 2 ns (Hankins et al. 2003). Even if a small fraction of γ-rays could be identified to originate from giant pulses vastly improved timing could be achieved. However, this suggestion is not supported by observations of the Crab pulsar (Lundgren et al. 1995), PSR B1937+21 (Cusumano et al. 2003), or PSR J0218+4232 (Knight et al. 2006).

3 PULSARS FOR PLACING LIMITS ON QUANTUM GRAVITY

Table 1. shows the current and future limits on $E_{\rm QG}$ potentially attainable using pulsars similar to the Crab pulsar and PSR B1937+21. The first two columns respectively show the pulsar and whether the limit shown is derived from an integrated pulse profile or the hypothetical correlation of γ-ray and radio giant-pulses. The third column shows the distance to the pulsar; and the fourth column shows the rms error expected for this sort of pulse. The last column shows the limit on $E_{\rm QG}$ attainable using 10 GeV photons.

But how realistic is it to detect and time such pulsars in the γ-ray band? EGRET marginally detected the MSP J0218+4232 in several days of integration (Kuiper et al. 2000). The distance to PSR J0218+4232 is 5.85 kpc (Manchester et al. 2005), and so with a sensitivity improvement of $\sim$50 GLAST should be able to detect similar MSPs to 40 kpc. Pulsars with narrower pulses are more readily detected, so MSPs in the Magellanic clouds probably can be detected. The flux from the Crab pulsar would be 1.2×10^5 times weaker if it were displaced to M31. Assuming that γ-ray pulsations from the Crab pulsar would have been detected if it was 16 times weaker (see Figure 12 of Ramanamurthy et al. (1995)), even extreme young pulsars in M31 that are 10 times stronger and 10 times faster than the Crab pulsar probably will not be detectable by GLAST.

Any extra-galactic pulsars detectable by GLAST or other future γ-ray missions will probably be detected in targeted observations with long integration times. Is it even possible to identify suitable pulsar targets using current radio-telescope technology? A simple extrapolation of the work of Knight et al. (2006) indicates that the CGSR2 baseband recorder at the 100 m Green Bank Telescope (GBT) can detect 5 Jyμs

[1] See: http://www-glast.stanford.edu

Table 1 Potential pulsar-derived limits on $E_{\rm QG}$

Pulsar	Limit type	Distance (kpc)	Estimated rms error (μs)	Limit on $E_{\rm QG}$ (GeV)
Crab	Integrated pulse profile	2	35	6×10^{16}
PSR B1937+21	Integrated pulse profile	3.6	10	4×10^{17}
Crab in M31	Integrated pulse profile	700	350	2×10^{18}
PSR B1937+21 in LMC	Integrated pulse profile	50	10	5×10^{18}
PSR B1937+21	Individual giant pulses	3.6	0.1	4×10^{19}

pulses using a 128 MHz band centred at 857 MHz with 250 ns sampling. About once per hour the Crab pulsar and PSR B1937+21 respectively emit giant pulses 125 and 100 times the mean pulse energy (Lundgren et al. 1995; Soglasnov et al. 2004). With respective flux densities at 857 MHz of 65 mJy and 39 mJy (Lorimer et al. 1995; Foster, Fairhead, & Backer 1991) and assuming any nebular contribution is insignificant, CGSR2 can detect the Crab pulsar to 460 kpc and PSR B1937+21 to 130 kpc. Although a blind search of M31 with integration times longer than 1 hr could be successfully carried out, it would require 2200 hrs of processing time on the completed 200 node Swinburne supercomputer for each hour of observation time. Use of an ideal telescope like FAST instead of the GBT would decrease total observing time for an equal-sensitivity survey by a factor of 25; and therefore also reduce computing by a factor of 25.

4 CONCLUSIONS

The best limits on the effective energy scale of quantum gravity obtained through observations of the travel time of high energy photons from pulsars are 10^2 times lower than those obtained using GRBs. Future γ-ray missions like GLAST will probably only be able to improve limits from the Crab pulsar by a factor of $\sim 10^2$. Good candidates for achieving further improvements are MSPs like PSR B1937+21, which emit giant radio-pulses and X-rays over narrow phase ranges. Crab-like pulsars in M31 also could provide better limits, but are probably too weak to detect in γ-rays. These pulsars are probably detectable through their emission of giant pulses in the radio band, although such a search would have enormous computing requirements.

Acknowledgements M. Bailes and R. Manchester are thanked for their comments on the manuscript. The support of a CSIRO Postgraduate Student Research Scholarship is acknowledged.

References

Amelino-Camelia G., Ellis J., Mavromatos et al., 1998, Nature, 393, 763
Boggs S. E., Wunderer C. B., Hurley K., & Coburn W., 2004, ApJ, 611, L77
Burgess C. P., Cline J. M., Filotas et al., 2002, Journal of High Energy Physics, 3, 43
Cusumano G., Hermsen W., Kramer et al., 2003, A&A, 410, L9
de Naurois M., Holder J., Bazer-Bachi R. et al., 2002, ApJ, 566, 343
Ellis J., Farakos K., Mavromatos et al., 2000, ApJ, 535, 139
Ellis J. R., Mavromatos N. E., & Sakharov A. S., 2004, Astroparticle Physics, 20, 669
Fierro j. M., Michelson P. F., Nolan P. L., & Thompson D. J., 1998, ApJ, 494, 734
Foster R. S., Fairhead L., & Backer D. C., 1991, ApJ, 378, 687
Hankins T. H., Kern J. S., Weatherall J. C., & Eilek J. A., 2003, Nature, 422, 141
Jacobson T., Liberati S., & Mattingly D., 2003, Nature, 424, 1019

Kaaret P., 1999, A&A, 345, L32
Knight H. S., Bailes M., Manchester R. N. et al., 2006, ApJ, 653, 580
Kuiper L., Hermsen W., Verbunt et al., 2000, A&A, 359, 615
Lorimer D. R., Yates J. A., Lyne A. G., & Gould D. M., 1995, MNRAS, 273, 411
Lundgren S. C., Cordes J. M., Ulmer M. et al., 1995, ApJ, 453, 433
Manchester R. N., Hobbs G. B., Teoh A., & Hobbs M., 2005, AJ, 129, 1993
Ramanamurthy P. V., Bertsch D. L., Fichtel et al., 1995, ApJ, 450, 791
Romani R., 2003, in Radio Pulsars, ed. M. Bailes, D. J. Nice, & S. Thorsett (San Francisco: ASP), 331
Rutledge R. E., Fox D. W., Kulkarni et al. , 2004, ApJ, 613, 522
Soglasnov V. A., Popov M. V., Bartel et al., 2004, ApJ, 616, 439